Microwave Radiation Characteristics of Relativistic Magnetron with Coupled Cavities

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Abstract – In the paper a novel method of increasing relativistic magnetron microwave radiation stability is described. It is based on insertion of external coupling into magnetron oscillatory system. The results of experimental research of the influence of waveguide coupling circuit with common radiator parameters on characteristics of *S*-band magnetron generation process is discussed. It's shown, that by tuning the channel electrical length it is possible both to amplify and slacken basic oscillation mode stability and considerably change spectrum and energy parameters of microwave pulses.

1. Introduction

At the present stage of microwave electronics development, high power radiation sources based on relativistic generating devices become more and more applicable [1]. Their practical application is restricted mainly by high cost of high power microwave radiation generation, by short lifetime of generating structure elements and, quite often, by low consumer characteristics of radiation: wide spectral width and low repeatability of pulse parameters. There are different ways to solve the above problems. These ways are usually based on using stabilizing elements that are typical for classical vacuum electronics [2]. The authors of this article have suggested an unusual method to increase stability of microwave radiation parameters of relativistic magnetron [3, 4]. This method is based on inserting external couplings into magnetron oscillatory structure. In this case, magnetron radiation characteristics are mainly defined by coupling parameters.

This work presents results of experiments conducted to investigate the influence of external coupling of relativistic magnetron cavities upon frequency and power characteristics of radiation. It is shown, that changing coupling parameters allows receiving microwave pulses with considerably different characteristics.

2. Experimental Equipment

Well-known advantages of cross-field devices predetermined interest of specialists in the field of relativistic HPM electronics. Frequency and phase stability of generated radiation, high efficiency, small dimensions and weight, low cost, low level of unwanted oscillations and harmonics were the reasons for intensive investigation of relativistic magnetrons. First experiments conducted in Massachusetts Institute of Technology (USA) and Applied Physics Institute at Academy of Sciences (USSR) as well as in Nuclear Physics Institute at TPU allowed getting power levels from hundreds megawatts to gigawatts with 10–30% efficiency.

First experiments conducted in NPI at TPU with relativistic magnetron in pulse periodic regime stimulated development of investigations in this direction [5]. Relativistic magnetrons generate in this experiments group of 3 pulses with pulse repetition rate of 160 pps. There was high repeatability of the HPM pulses waveform and small pulse shortening compared to current pulse of a linear induction accelerator. Output parameters are: HPM power – 360 MW, current – 3.6 kA, voltage – 300 kV. In 1989 a mobile version of the pulse-periodic relativistic magnetron was produced with the following output parameters: pulse repetition rate in a continuous mode – 20 Hz, HPM power ~ 200 MW, current 3 kA, voltage – 300 kV. The peculiarity of the system is common power supply for LIA and magnetic system. In the experiments described above the source of power supply for relativistic magnetron were sections of linear induction accelerators with multi-channel spark-gaps. In the beginning of 90s NPI developed LIA based on magnetic elements. The magnetic elements, which is a saturation-core chokes, can switch a current of hundreds of kiloamperes at a frequency of a few kilohertz and has an almost unlimited service life. In order to minimize the overall dimensions of such a switch and, correspondingly, its inductance, the forming lines should be charged from magnetic pulsed generators (MPG) in time intervals of hundreds of nanoseconds. Their distinguishing feature was higher repetition rate and possibility to form bursts containing more pulses. The development of a compact power supply unit for relativistic magnetrons resulted in a design of the accelerator arrangement with all elements located in a common housing, making it possible to reduce the inductance in the connections of the components, increase the reliability, and reduce the weight and dimensions of the facility – LIA 04/4000 and LIA 04/6. This class of accelerators is presented in detail in [5, 6].

3. Experimental Scheme

Structural schematics of experimental layout is given in Fig. 1. Two opposite resonators of the 6-cavity S-band magnetron 1, which is supplied from the linear induction accelerator 2, are coupled by the waveguide coupling channel 3 through tapered sections 4 and a 3 dB waveguide H-tee-joint 5, which is placed on electrical symmetry axis of the coupling channel. The T-joint provides microwave power extraction from the coupling channel through the radiating pyramidal antenna 6. The insets 7 allow discrete adjusting of the waveguide coupling channel total length.

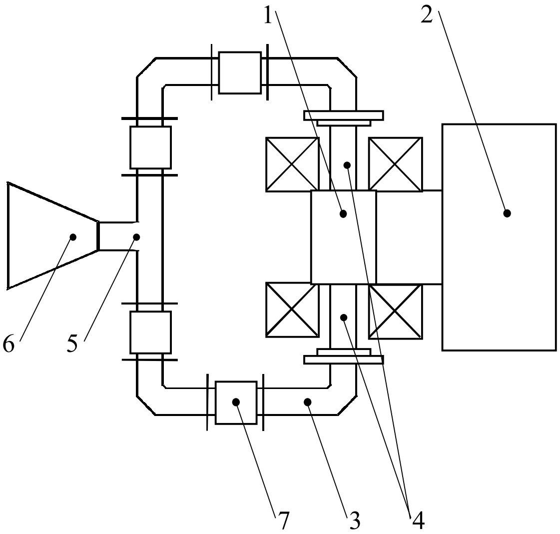

Fig. 1. Schematic of the experiment

Experimental system [5] generates microwave pulses with repetition frequency up to 320 Hz at cathode-anode voltage of 350–480 kV, full current 2.5–4 kA and it is also distinguished by high repeatability of performance characteristics. In the experiment we defined power and spectrum content of microwave pulses; full energy for the pulse was calculated in accordance with signal envelope. To measure radiation parameters, we used amplitude detectors and tunable narrow band filter. For spectrum measurements, we made up to 750 shots at different fixed resonant frequencies of the filter. This allowed making quality investigation of spectrum content of the relativistic magnetron radiation, reducing possible error and getting statistics for future investigation.

4. Results and Discussion

The main oscillatory type in the investigated relativistic magnetron is π-mode. For this mode, the oscillations of the opposite resonators with respect to the output waveguides are in-phase. That is why they are summed up in the common radiator in case it is symmetrically inserted into the coupling channel. If the coupling channel's length is adjusted in such a way, that signals at its inputs are in-phase with resonators oscillation, the basic mode will get stabilized. At different lengths of the coupling channel and phase relations we can expect magnetron operating regime to get destabilized. Presence of the coupling channel also straightens amplitude and phase of high frequency field in the opposite sectors of magnetron interaction space; it also improves energy interchange between electrons and microwave field.

Experiments were made with two different source configurations: magnetron with non-coupled resonators and magnetron with coupled resonators and symmetrically placed radiator. For the last configuration the total electrical length of the coupling channel was tuned from 1800 to 2000 mm (in 20 mm steps). This allowed setting different phase delays of signals in the coupling channels.

Investigation results for the magnetron with non-coupled resonators are given in Fig. 2.

Microwave pulses from each outlet (Fig. 2.1a) have power of ~190 MW, pulse energy is ~4.8 J. Spectral width at – 3 dB level of the magnetron (Fig. 2.1b) is ~ 120 MHz wide. The spectrum is quite noised. This shows general instability of generation process.

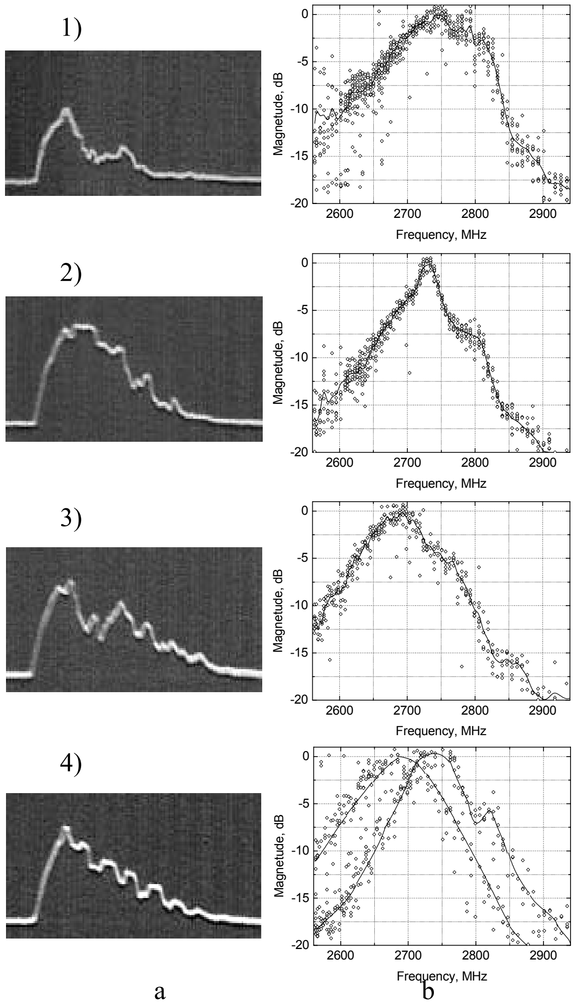

Fig. 2

After we coupled the magnetron resonators, we successively searched for optimum length of the coupling channel. Key results of this experiment are given in Fig. 2.2–2.4. During the search we identified three rather wide regions with evidently different frequency spectrum and microwave pulse shape. These regions are about 40 cm from each other on the channel length, which makes it 1/4 of the wavelength for the operating mode. They also repeat in regular intervals when we extend the coupling channel's length by 1 wavelength (~ 170 mm). This allows connecting the above regions with optimal and non-optimal way of resonator oscillations interaction.

In the region of optimal interaction the microwave pulse power (see Fig. 2.2a) is much higher than the power at the outlet of the magnetron with non-coupled resonators, it is ~ 425 MW at pulse energy of ~17.6 J. Spectral width wide at –3 dB level (see Fig. 2.2b) is ~35 MHz and there is much less noise. In the region half a wavelength from the optimum, the microwave pulse envelopes (see Fig. 2.3a) are jagged; this reflects instability of generation process caused by anti-phase resonator oscillations and coupling signals. Power here is ~ 390 MW, pulse energy ~ 12.3 J, spectral width at –3 dB level exceeds ~ 90 MHz.

Very interesting is the intermediate region. It corresponds to those channel lengths where coupling signals and resonator oscillations are in quadrature. The peculiarity of this area is that magnetron radiation spectrum splits into 2 parts (Fig. 2b). The spectral widths at –3 dB level in this case are not wider than 150 MHz, power and energy are ~ 377 MW and ~ 15.2 J respectively. The observed spectrum view shows equiprobable from pulse to pulse excitation of magnetron at those frequencies, where in-phase interaction of oscillations at resonators outlets is realized.

Figure 3 demonstrates the measurement results of frequency peaks position for all experiments carried out with coupled resonators. Cyclic nature of the areas mentioned is clearly illustrated.

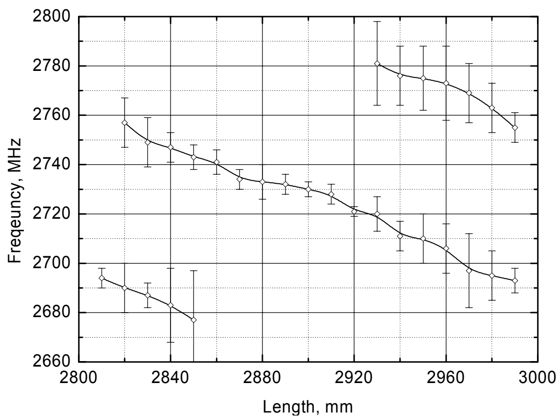

Fig. 3

5. Calculation of the Magnetron Frequency

The obtained experimental results are going to be explained by using an equivalent circuit of the magnetron in question.

The circuit is represented by identical resonant parallel contours (L_0, C_0) and capacitances, separating these contours C_k; G_0 is contours conductivity:

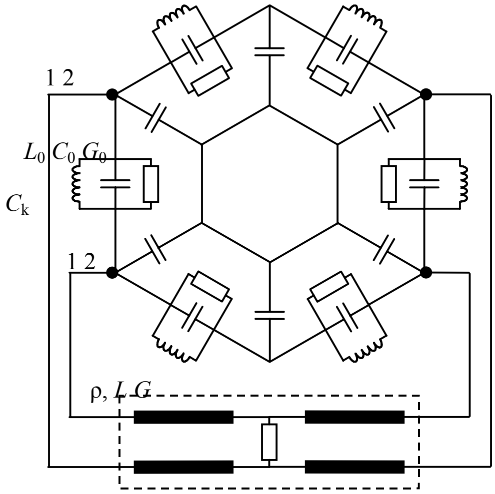

Fig. 4

The coupling circuit is connected to poles 1–1 and 2–2 of two opposite oscillatory circuits, and complies with the scheme of the actual experiment. The values ρ and L represent wave impedances and length of the transmission line section respectively, G is the conductivity of the common load.

Eigenfrequencies of oscillation modes calculated for a magnetron without the coupling circuit are as follows:

$$f_{\pi,\,0} = 3052.3 \text{ MHz}, f_{2\pi/3,\,0} = 3018.5 \text{ MHz}.$$

It can be seen that the difference between π and 2π/3 oscillation modes equals to only ~ 1%. In course of the actual experiment without external coupling of resonators, it causes mode competition and lowers energy and spectral characteristics of generator's radiation (Fig. 2.1).

It is possible to estimate the influence of coupling circuits on frequency spectrum by calculating the resonant frequencies of the four-pole 1–2. Resonant frequencies are calculated from the condition that imaginary components of system's input conductance from the side of given pole equal to zero. Magnetron's ring circuit reduces to a simple cascade circuit by symmetry transformation.

Then system's input dynamic conductivity under equal-amplitude excitation can be calculated as follows:

$$Y_{\text{in}} = Y_{11} + Y_{12} \exp(j\Delta\varphi),$$

where Y_{11}, Y_{12} are parameters of the conductivity matrix of magnetron four-poles and coupling circuit parallel connection; Δφ is input voltage phase difference. For the 6-cavity magnetron in question, π-mode is the main operating oscillation mode, and a competing mode closest to it is the 2π/3-mode. Therefore, due to system's azimuthal symmetry Δφ = 0 and π, respectively.

If the common load is matched ($G = 2/\rho$), then input conductivity for π-mode is purely real and f_π does not shift in relation to $f_{\pi 0}$. The $f_{2\pi/3}$ frequency, on the contrary, is prone to pulling, as a dynamic short-circuiting occurs in the common load plane.

Figure 5 shows magnetron's frequencies behavior in relation to coupling circuit length when common load is mismatched: $G = 1/\rho$.

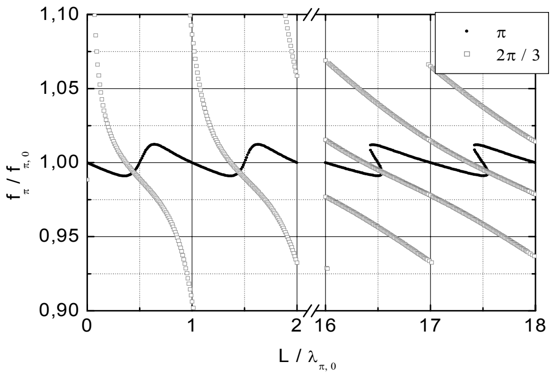

Fig. 5

The presented dependencies have the cyclic character. It is worth noticing that overlapping areas can be seen on the graph for π-mode. Two stable frequencies are present within these areas; their presence depends on the length of coupling circuit. These frequencies are the sub-modes of π-mode oscillations. Medium frequency is not stable.

This phenomenon was discovered in course of the experiment: under condition of the above mentioned mismatching that takes place in two-valued areas, random pulse-to-pulse excitation of one or another sub-mode alternately occurs. Their frequencies difference equals to 70 ± 5 MHz (Fig. 3).

It can be seen that this calculation provides quite accurate quantitative evaluation. It also points out another valuable feature: even if coupling circuit length is substantial, frequency separation of oscillation modes π and 2π/3 increases (up to 1.5–2%). For short lengths of coupling circuits this separation may reach considerable values (of 5% and more).

6. Conclusion

Thus, based on the results of conducted experiments, we can draw a conclusion that using external coupling of relativistic magnetron resonators makes considerable impact on stability of operating mode. The suggested original variant to control generation process parameters in relativistic magnetron allows using the described layout to make highly stable sources of high power microwave radiation for different applications.

The following modifications were made to provide the capability of continuous operation at high repetition rate: 1) The LIA module has the magnetic switch and magnetic pulsed generator for the strip-line pulse forming network commutation and charging. 2) The LIA module power supply system contains three-phase voltage source with the primary storage oscillatory charging, stabilization circuit for the primary storage voltage level, and thyristor commutator. 3) The relativistic magnetron (I) is of increased resistivity to the anode block damage from the anode current electron bombardment, (II) is adapted to the LIA module voltage pulse shape. 4) The magnetic system of the magnetron (Helmholtz pair) is supplied from the dc current source and made of copper tube of square cross-section with the central hole for cooling water transport. The electromagnet provides the magnetic field of 0.55 T continuously. The installation control system allows one to set the magnitude of the primary storage voltage, number of shots in a burst, and pause between bursts.

The repetitively-pulsed relativistic magnetron generates microwave pulses of highly reproducible amplitude and waveform. The peak power of 425 MW in the S-band frequency (2840 MHz, < 1.3% spectral width at –3 dB level) at 45 ns FWHM pulse duration is produced with 460 kV cathode voltage and 2,8 kA current in the continuous operation mode (0–8 Hz rep-rate frequency), repetitively-pulsed mode (8–80 Hz), and burst mode (80–320 Hz). Power extraction from relativistic magnetron is performed with the help of rectangular waveguide (standard section) when a lower-order wave H_{01} is excited. This circumstance allows transferring electromagnetic energy almost without any loss and effectively employing horn antennas to form required radiation pattern. It is possible to use a system of radiators, which are installed as coupling channel to increase power flow density.

Introducing the coupling circuit of magnetron resonators may improve the frequency separation of oscillation modes, which in turn, increases the stability of basic operating π-mode. This improves energetic characteristics of the radiation source.

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